Jet Propulsion Laboratory
California Institute of Technology

50,000 Laps Around Mars: Navigating the Mars Reconnaissance Orbiter Through the Extended Missions (January 2009 – March 2017)

Premkumar R. Menon

Sean V. Wagner, Stuart Demcak, David C. Jefferson, Eric J. Graat, Kyong J. Lee, and William B. Schulze

ISTS/ISSFD Symposium
Matsuyama, Japan
3-9 June 2017
ISSFD Paper 2017-110

Mars Reconnaissance Orbiter Project

Mars Reconnaissance Orbiter (Mission, Spacecraft and PSO)

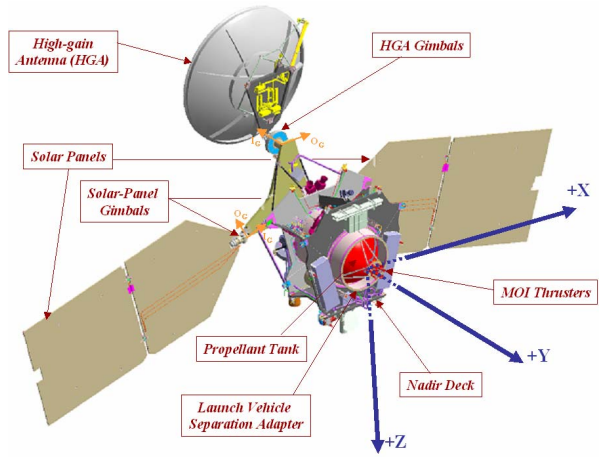
MRO launched in August 2005 from Cape Canaveral Air Force Station arriving at Mars in March 2006 and started science operations in November 2006. It has completed 10 years since launch (50,000 orbits by March 27, 2017) and to date returned more than 300 Terabytes of data.

MRO Primary Science Orbit (PSO):

- **Sun-synchronous** orbit ascending node at 3:00 PM $\pm$ 15 minutes Local Mean Solar Time (LMST) (daylight equatorial crossing)
- Periapsis is **frozen** about the Mars South Pole
- **Near-repeat ground track walk (GTW)** every 17-day, 211 orbit (short-term repeat) MRO targeting cycle, exact repeat after 4602 orbits. The nominal GTW is 32.45811 km West each 211 orbit cycle (maintained with periodic maneuvers)

MRO Spacecraft:

- **Spacecraft Bus:** 3-axis stabilized ACS system; 3-meter diameter High Gain Antenna; hydrazine propulsion system
- **Instrument Suite:** HiRISE Camera, CRISM Imaging spectrometer, Mars Climate Sounder, Mars Color Imager, Context Camera, Shallow Subsurface Radar, Electra engineering payload (among other instrument payloads)



MRO Mission Overview

- The MRO Navigation Team has supported science operations and relay for landed assets on Mars for over 10 years
  - Science Operations since November 2006
  - Primary Science Phase (1/2007 – 12/2008)
    - Phoenix Lander EDL Support
  - Extended Science Phase (1/2009 – 9/2010)
  - Extended Mission – 1 (10/2010 – 9/2012)
    - Mars Science Lander EDL Support
  - Extended Mission – 2 (10/2012 – 9/2014)
    - Comet Siding Spring Risk Mitigation Preparation
  - Extended Mission – 3 (10/2014 – 9/2016)
    - Comet Siding Spring Close Approach
  - Extended Mission – 4 (10/2016 – 9/2018)
    - ExoMars Schiaparelli Overflight Support
    - InSight EDL Preparation

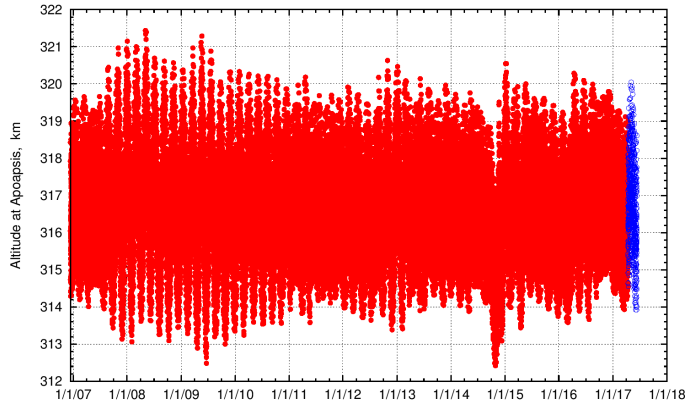
MRO Navigation Requirements

	Position - 3σ		
	Downtrack	Radial	Crosstrack
Short-Term Predict	1.5 km	40 m	50 m
Long-Term Predict	195 km (3°)	—	—
Reconstruction	100 m	1.5 m	40 m

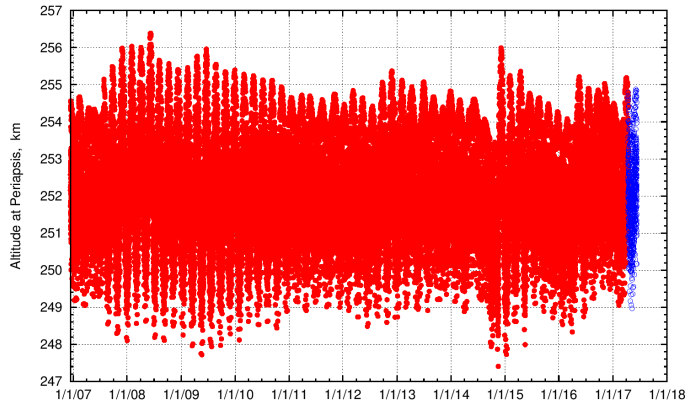
- Prediction
  - Short-term currently ∼5 days long
    - 1.5 km down-track error corresponds to 0.43 seconds timing accuracy
  - Long-term 28 days
    - 195 km down-track error corresponds to 59 seconds timing accuracy
- Reconstruction
  - Accuracy assessed by comparing overlaps between consecutive batches

MRO Osculating Orbit Parameters on March 27, 2017 (50,000th Orbit)

Periapsis Epoch: 27-Mar-2017 11:57:51.031 ET	
Semi-Major Axis (a)	3649.2801 km
Eccentricity (e)	0.0057
Inclination (i)	92.5787°
Argument of Periapsis (ω)	269.06956°
Right Ascension of Node (Ω)	235.7435°
True Anomaly (v)	0.0°
Additional Orbit Information	
Descending Equator Epoch (Start of 50,000th Orbit): 27-Mar-2017 11:30:23.949 ET	
Apoapsis Epoch: 27-Mar-2017 12:53:43.282 ET	
Period (T)	111.55 min
Periapsis Altitude (H_p)	252.1262 km
Apoapsis Altitude (H_a)	318.2174 km

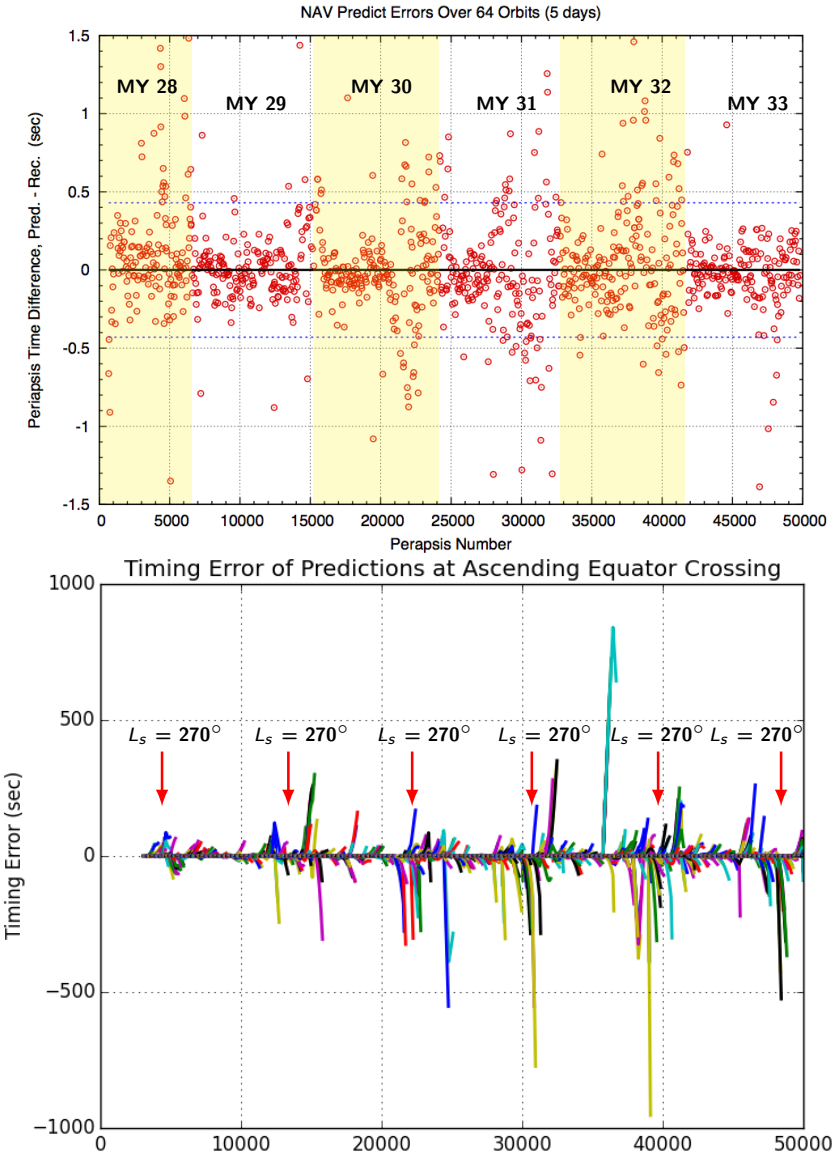


Apoapsis altitude (reconstructed in red, predicted in blue).



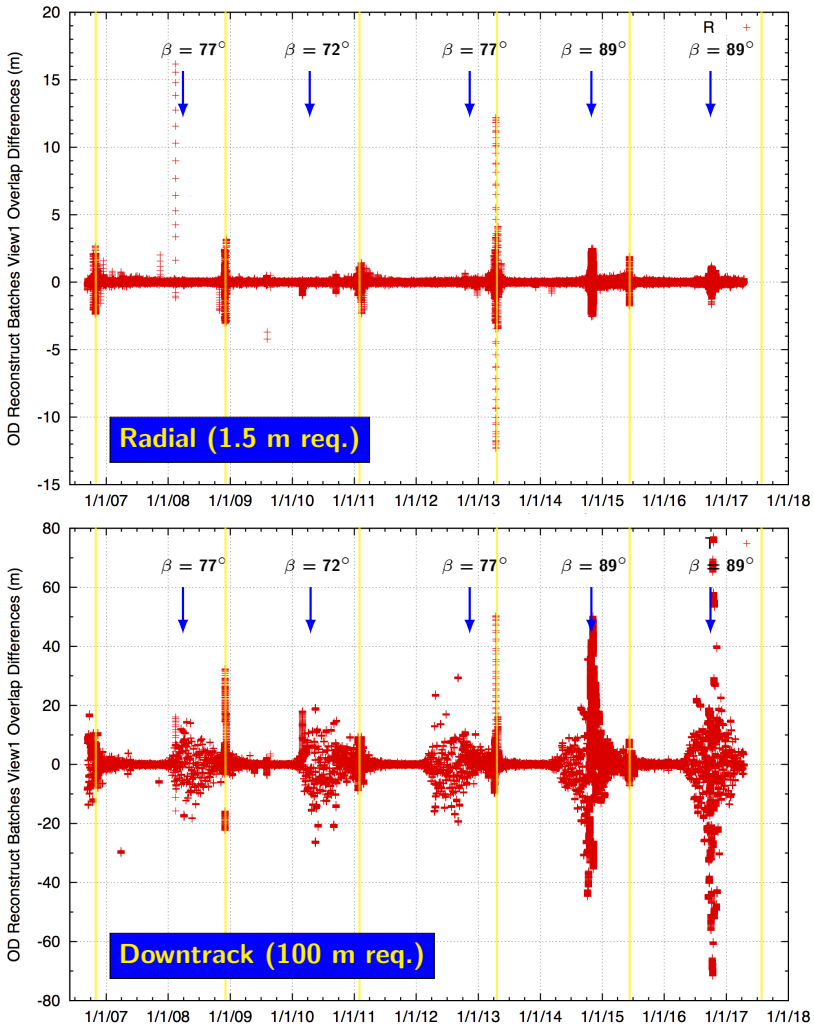
Periapsis altitude (reconstructed in red, predicted in blue).

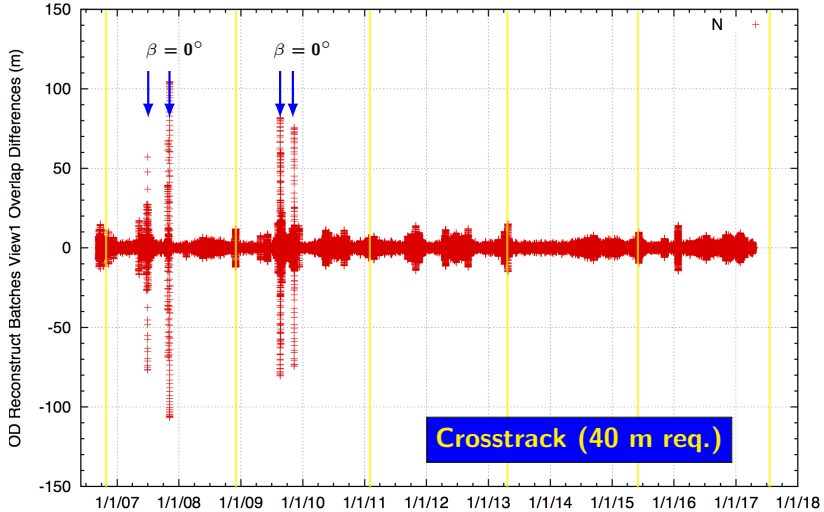
MRO Trajectory Prediction History

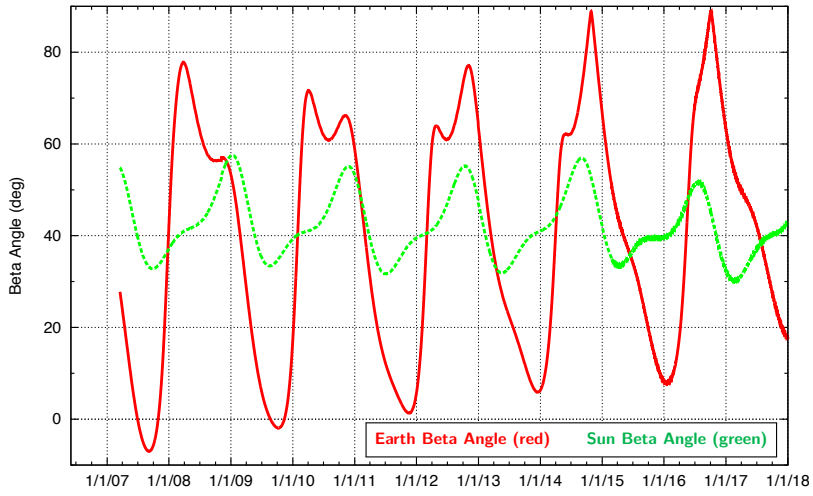


- Short-term prediction (∼5 days long)
  - 1.5 km down-track error corresponds to 0.43 seconds timing accuracy
- Long-term prediction (28 days long)
  - 195 km down-track error corresponds to 59 seconds timing accuracy

MRO Trajectory Reconstruction History





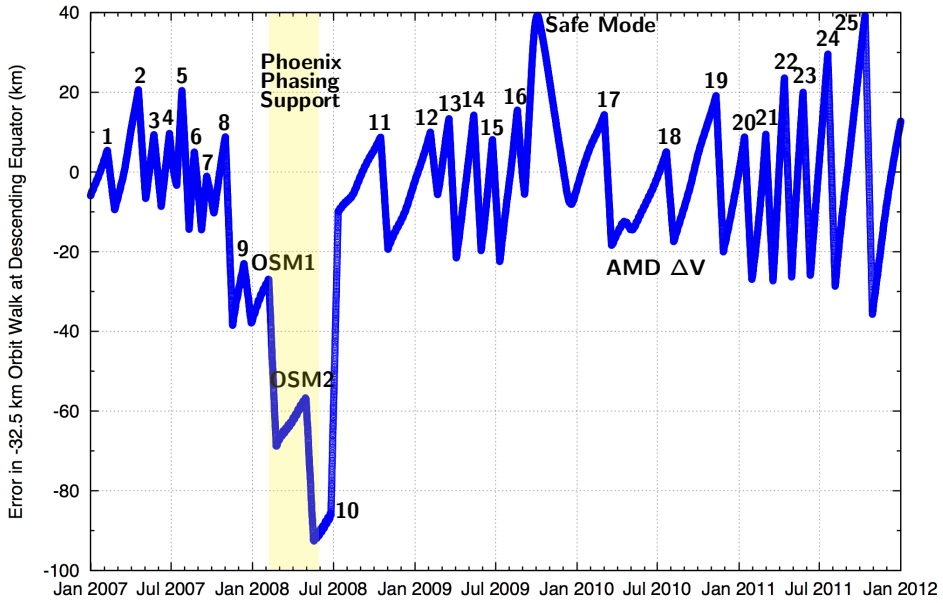


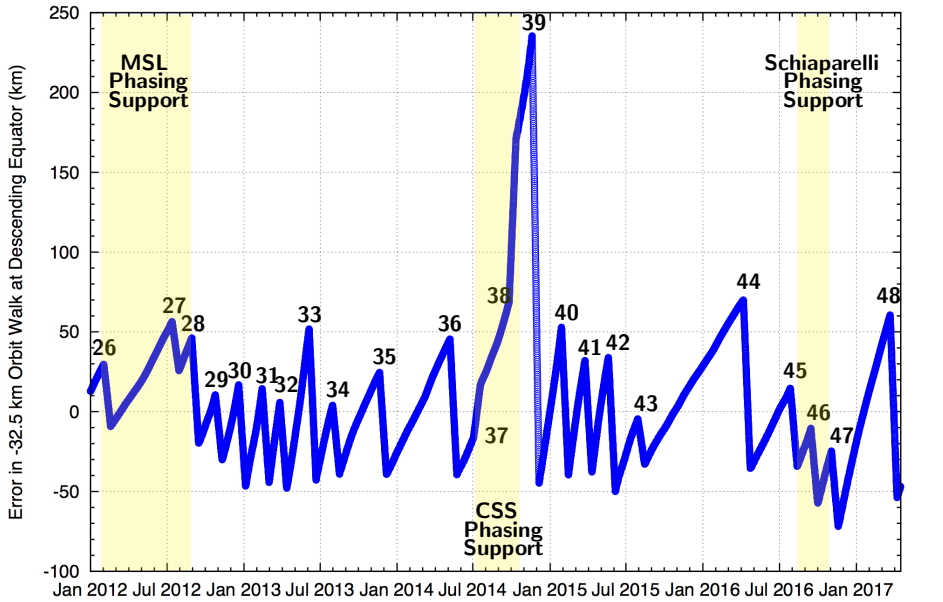
MRO Maneuver History & ΔVs

Orbit Trim Maneuver (OTM) #	Date	Apsis or Node	ΔV Mag. (m/s)
PSP — 01-Jan-2007 to 31-Dec-2008			
01	07-Feb-2007	Apo	0.0711
02	18-Apr-2007	Peri	0.1302
03	23-May-2007	Apo	0.1128
04	27-Jun-2007	Peri	0.1230
05	25-Jul-2007	Apo	0.2248
06	22-Aug-2007	Peri	0.1416
07	19-Sep-2007	Apo	0.0816
08	31-Oct-2007	Peri	0.1925
09	12-Dec-2007	Apo	0.0764
OSM-1	06-Feb-2008	Peri	0.1520
OSM-2	30-Apr-2008	Peri	0.1223
10	25-Jun-2008	∼Apo	0.2485
11	15-Oct-2008	Peri	0.1078
ESP — 01-Jan-2009 to 30-Sep-2010			
12	**04-Feb-2009**	**DEq**	**3.1943**
13	18-Mar-2009	Peri	0.1525
14	13-May-2009	Peri	0.1627
15	24-Jun-2009	Peri	0.1589
16	19-Aug-2009	Peri	0.1315
17	03-Mar-2010	Peri	0.1235
18	21-Jul-2010	Peri	0.0940
EM1 — 01-Oct-2010 to 30-Sep-2012			
19	10-Nov-2010	Peri	0.1543
20	13-Jan-2011	Peri	0.1603
21	02-Mar-2011	Peri	0.2160
22	13-Apr-2011	Peri	0.2745
23	25-May-2011	Peri	0.2364
24	20-Jul-2011	Peri	0.2666
25	12-Oct-2011	Peri	0.2923
26	01-Feb-2012	Peri	0.1521
27	13-Jul-2012	Peri	0.1305
28	29-Aug-2012	Peri	0.2591
EM2 — 01-Oct-2012 to 30-Sep-2014			
29	24-Oct-2012	Peri	0.1830
30	19-Dec-2012	Apo	0.2953
31	13-Feb-2013	Peri	0.2957
32	27-Mar-2013	Peri	0.2834
33	05-Jun-2013	Peri	0.4011
34	31-Jul-2013	Apo	0.1990
35	20-Nov-2013	Peri	0.2411
36	07-May-2014	Peri	0.3092
37	02-Jul-2014	Peri	0.0649
38	25-Sep-2014	Apo	0.2773
EM3 — 01-Oct-2014 to 30-Sep-2016			
39	**19-Nov-2014**	**DEq**	**3.4597**
40	28-Jan-2015	AEq	0.4342
41	25-Mar-2015	Peri	0.3239
42	20-May-2015	Apo	0.3530
43	**29-Jul-2015**	**DEq**	**5.3401**
44	**06-Apr-2016**	**AEq**	**7.9166**
45	27-Jul-2016	Peri	0.1921
46	14-Sep-2016	Peri	0.2102
EM4 — 01-Oct-2016 to 30-Sep-2018			
47	02-Nov-2016	Apo	0.2241
48	**22-Mar-2017**	**DEq**	**3.2032**

- Orbit Change Maneuvers (OCMs)
  - Out-of-plane ΔV
  - OTMs 12, 39, 43, 44 & 48
  - LMST control
- Orbit Synchronization Maneuvers (OSMs)
  - Along velocity vector
  - OSM1, OSM2, OTMs 26, 27, 37, 38, 45 & 46
  - Phasing control
- All other Orbit Trim Maneuvers (OTMs)
  - Pro-velocity vector
  - Ground track walk control
  - Frozen condition maintenance

MRO Ground Track Walk History





Primary Science Phase (PSP):

- Maintain the PSO GTW repeat error between ±10 km (OTMs 1–10)
- Exceptions were OTMs 08-09 and OSMs 1-2 for Phoenix EDL phasing

Phoenix EDL:

- Pro-velocity phasing maneuvers to EDL
- Anti-velocity maneuver to return to PSO
- **GTW error:** about −90 km

Extended Science Phase (ESP):

- Maintain the PSO GTW repeat error between ±20 km (OTMs 11–19)
- Exception was safe mode activity which brought GTW repeat error from +40 km to about −10 km

Extended Missions 1-3 (EM1-EM3):

- Maintain the PSO GTW repeat error between ±30 km (OTMs 20–23)
- Maintain the PSO GTW repeat error between ±40 km (OTMs 24–47)
- Exceptions were OTMs 26-27, 37-38, and 45-46 for MSL, CSS, and Schiaparelli phasing

MSL EDL:

- Pro-velocity phasing maneuvers to EDL
- Pro-velocity maneuver to return to PSO
- **GTW error:** about +60 km

Comet Siding Spring (CSS) Flyby:

- Anti-velocity phasing maneuvers to safe location
- Pro-velocity maneuver to return to PSO
- **GTW error:** about +240 km (largest)

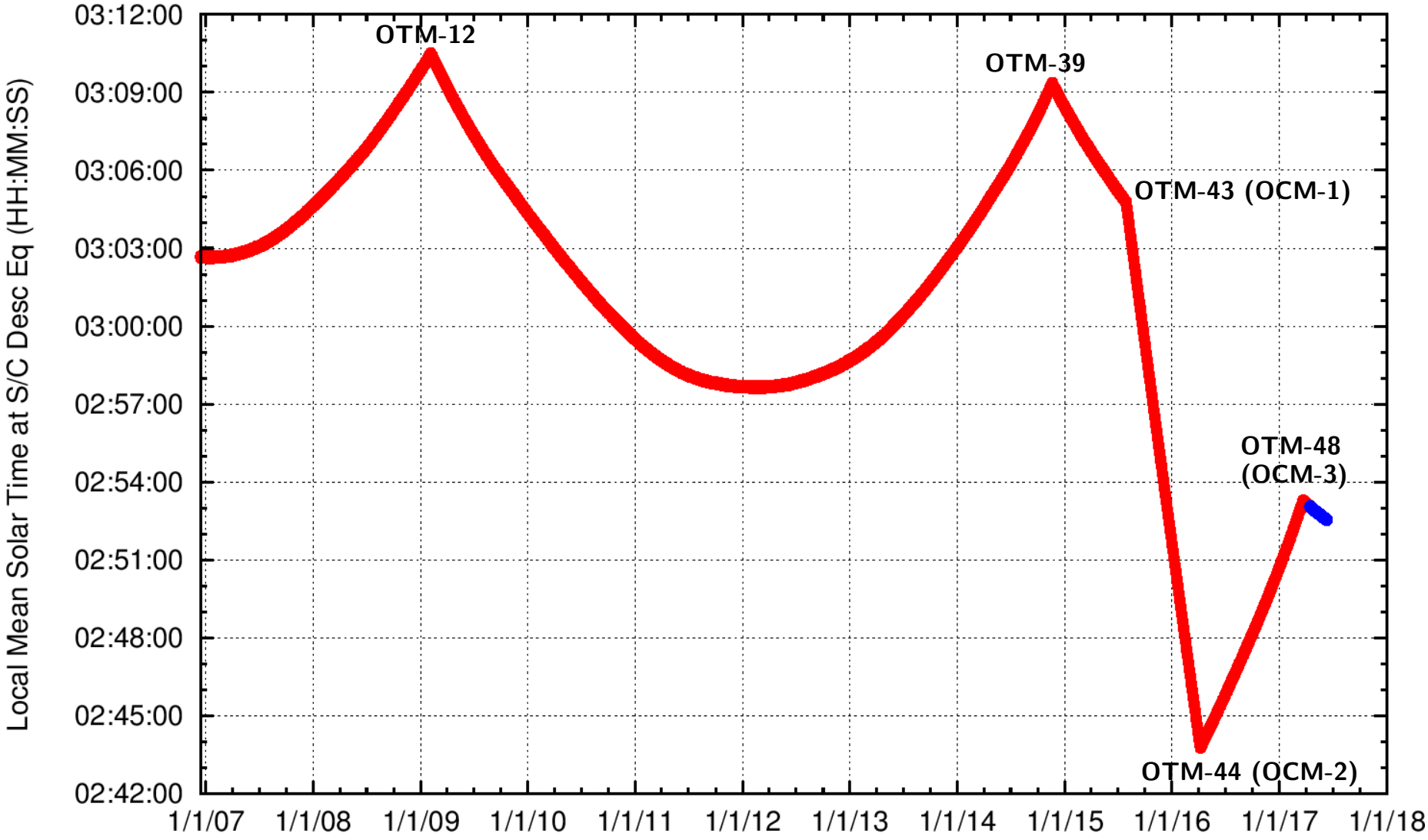
Schiaparelli Overflight:

- Pro-velocity phasing maneuvers to third overflight target
- Pro-velocity maneuver to return to PSO
- **GTW error:** about −60 km

MRO Phasing Offset Performance

Phasing Target	Phoenix EDL	MSL EDL	CSS Flyby Safe Location	Schiaparelli 3rd Overflight
(2000 IAU Mars Fixed)	25-May-2008	06-Aug-2012	19-Oct-2014	20-Oct-2016
Target Time (SCET)	23:32:07.0026 ET	05:11:54.5626 ET	20:07:00 UTC	17:17:43.7890 ET
Target Latitude	48.0311323 deg	−26.5011 deg	7.6042 deg	−2.05 deg
Pre-OSM Offset	**23.7 min early**	**48.9 min early**	**19.0 min late**	**30.6 min early**
OSM Location	OSM-1	OTM-26 (OSM-1)	OTM-37 (OSM-1)	OTM-45 (OSM-1)
OSM Correction	**20.7 min early**	**36.5 min early**	**9.0 min late**	**20.6 min early**
Post-OSM Offset	2.6 min early	12.4 min early	6.1 min late	9.5 min early
OSM Location	OSM-2	OTM-27 (OSM-3)	OTM-38 (OSM-2)	OTM-46 (OSM-2)
OSM Correction	**3.9 min early**	**3.8 min early**	**8.4 min late**	**9.6 min early**
Post-OSM Offset	2.5 sec early	11.3 sec late	23.7 sec early	2.5 sec late
Requirement	**±30 sec**	**±30 sec**	**±2 min**	**±5 min**
Final Phasing Offset	**0.25 sec early**	**9.0 sec late**	**57.0 sec early**	**10.4 sec late**
Comments	Low density. OTMs 08 & 09 used to reduce ∼45 min phasing offset.	Low density. Cancelled OSM-2 on 20-Jun-2012.	High density. Phasing target was arrival time of peak particle fluency.	High density. Phasing target was maximum elevation time at third overflight.

MRO LMST History & InSight Support Preparation



Drag ΔV per Orbit During High Density Seasons

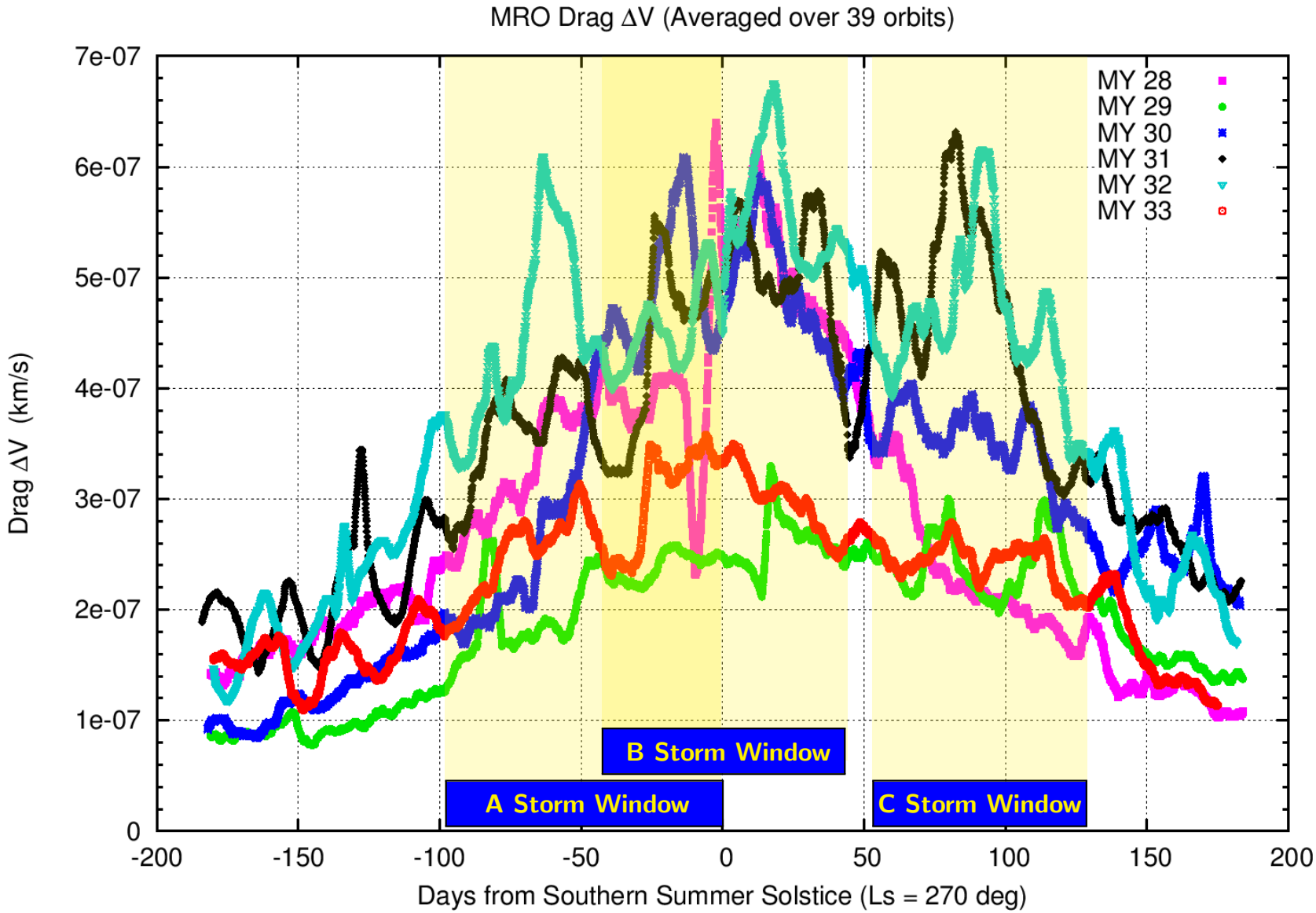
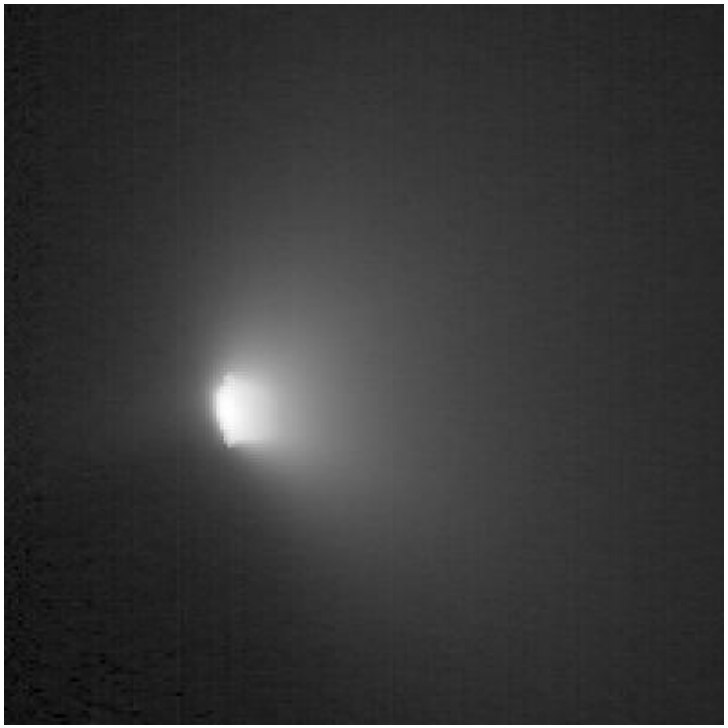


Image Highlights Taken by MRO's HiRISE Camera



Closest approach image of Comet Siding Spring taken by HiRISE Camera (nucleus saturated). October 19, 2014 18:24 UTC at a range of 139,000 km, 28×28 km field-of-view. Source: Alan Delamere.

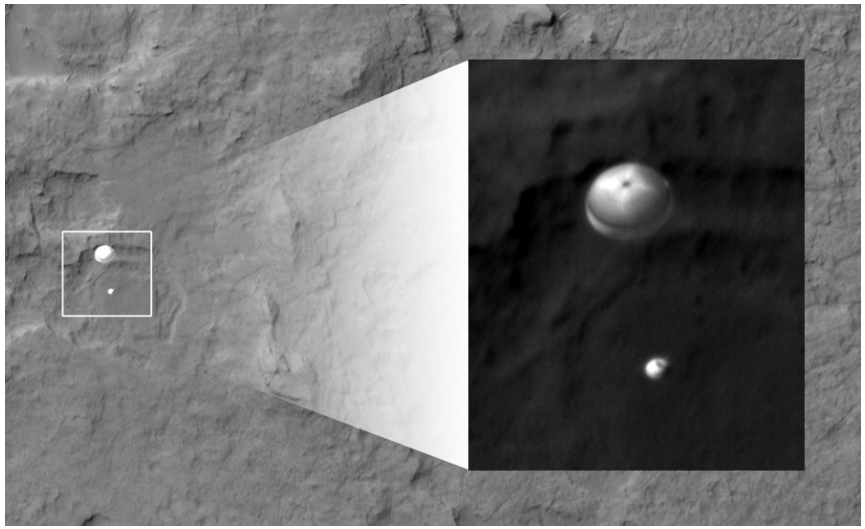
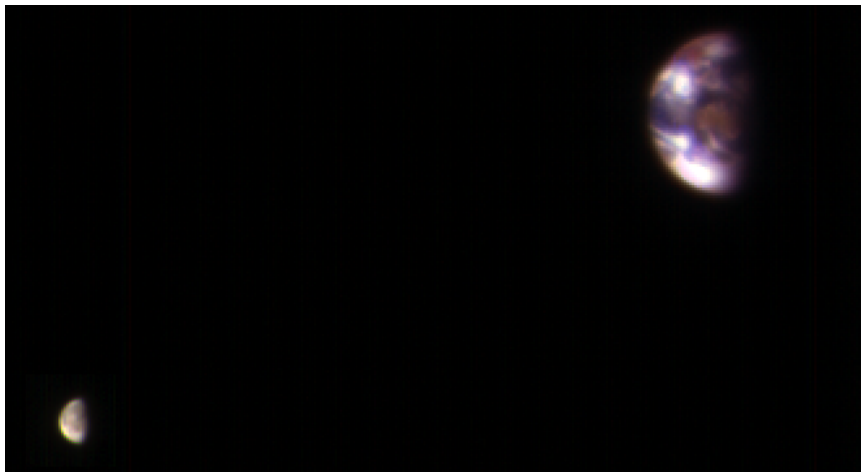


Image of MSL parachute landing taken by HiRISE Camera. Source: NASA/ JPL-Caltech.



Lunar calibration images of Earth and Moon taken by HiRISE Camera (IRB color). Source: NASA/JPL-Caltech.

Impact Site by MRO's CTX Camera Before Landing

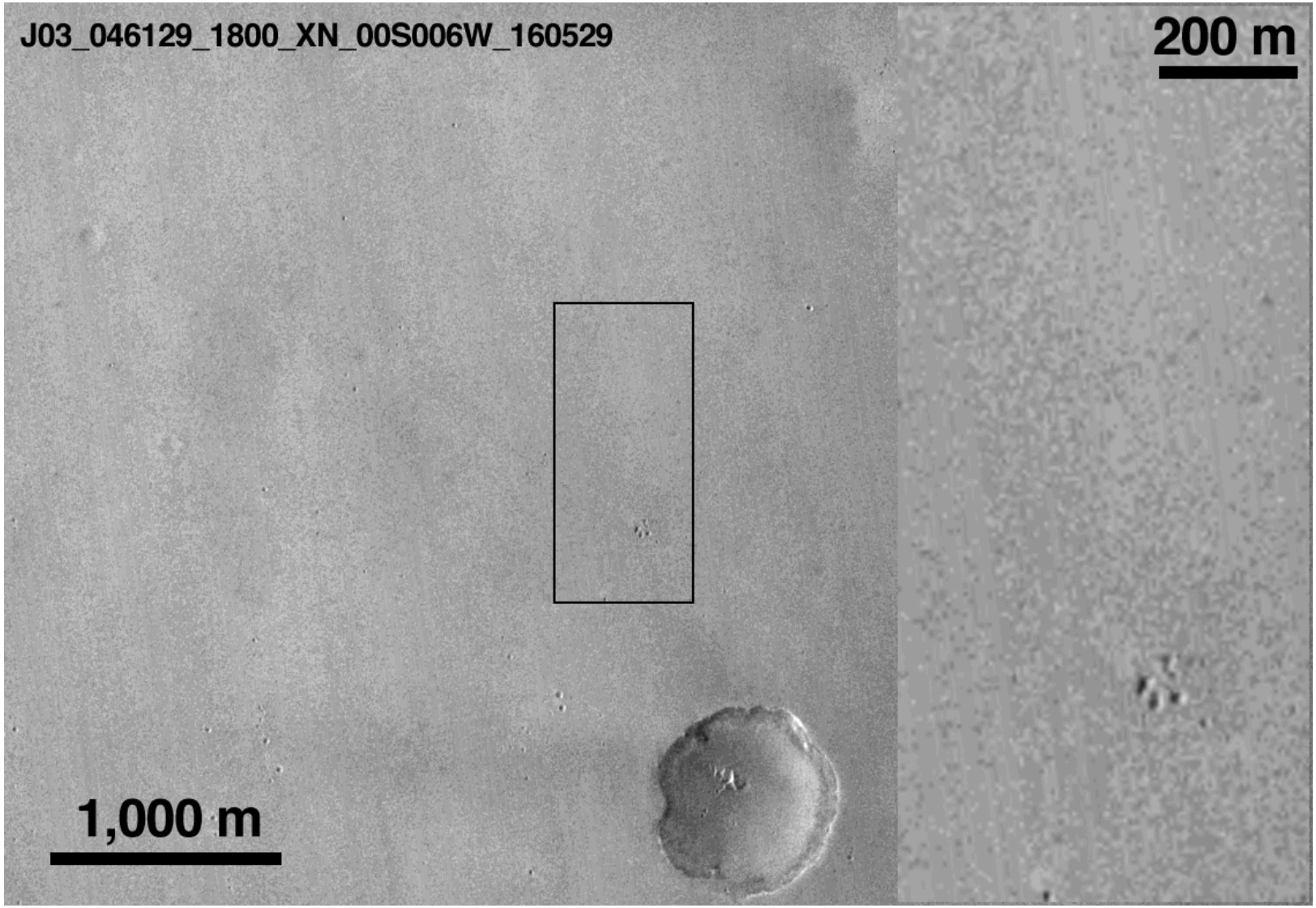


Image of Schiaparelli landing site taken by CTX before impact (May 29, 2016)

Impact Site by MRO's CTX Camera After Landing

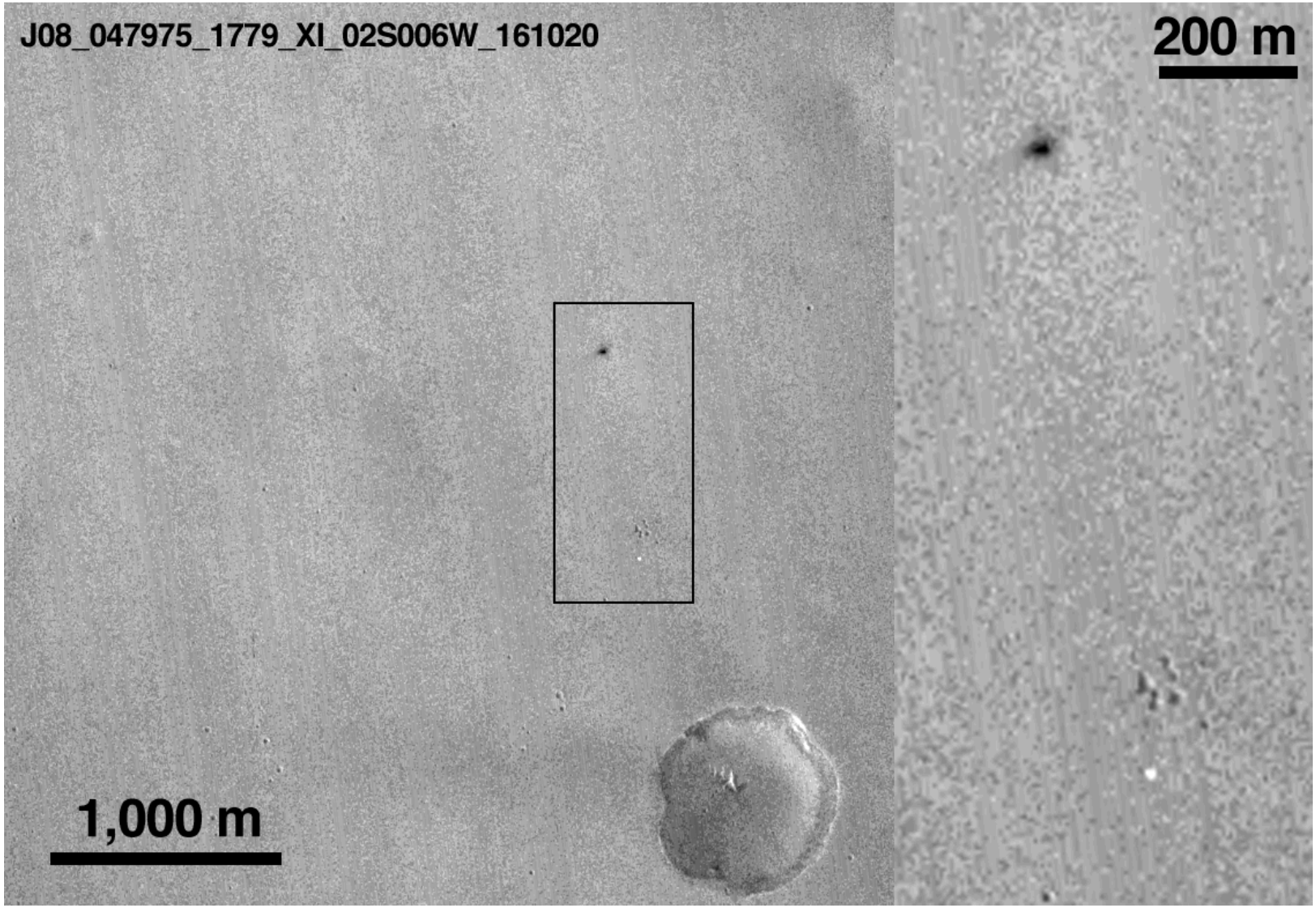
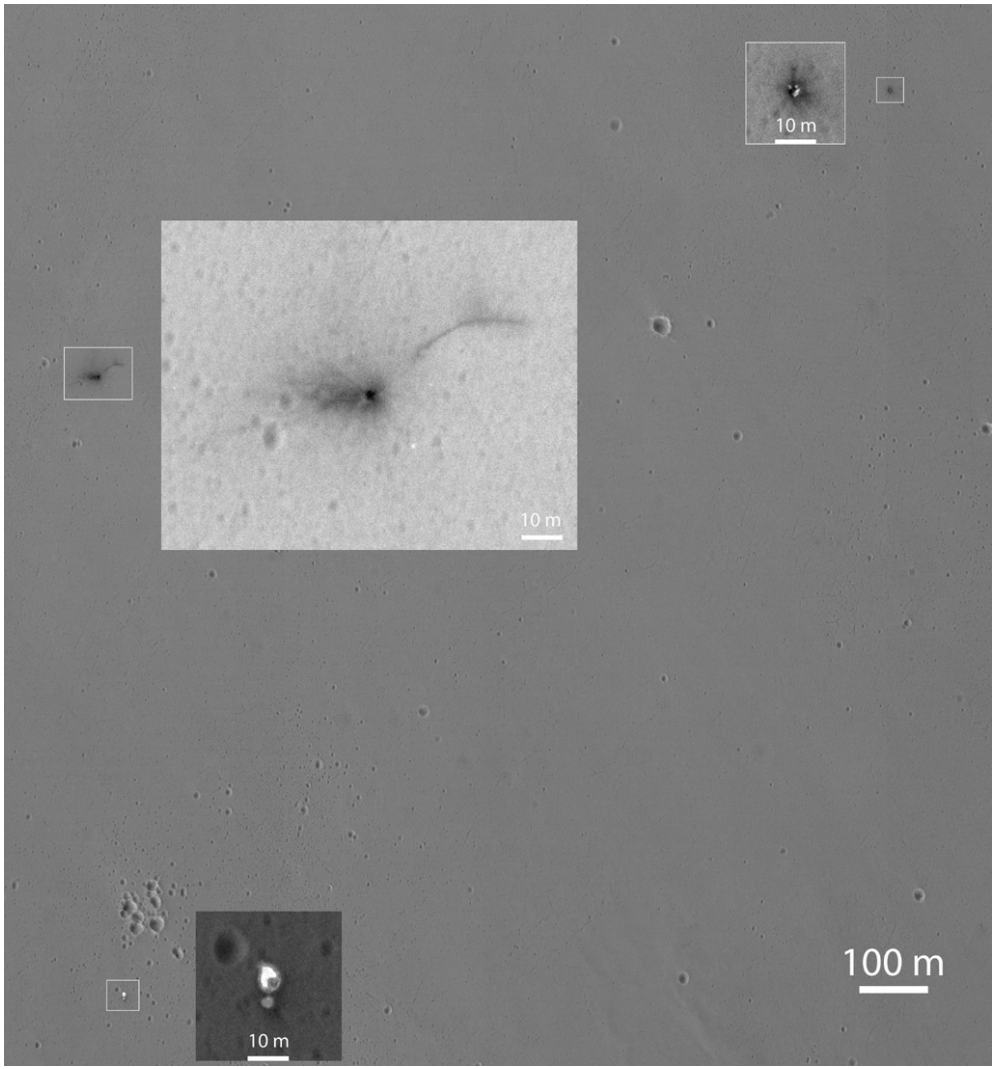
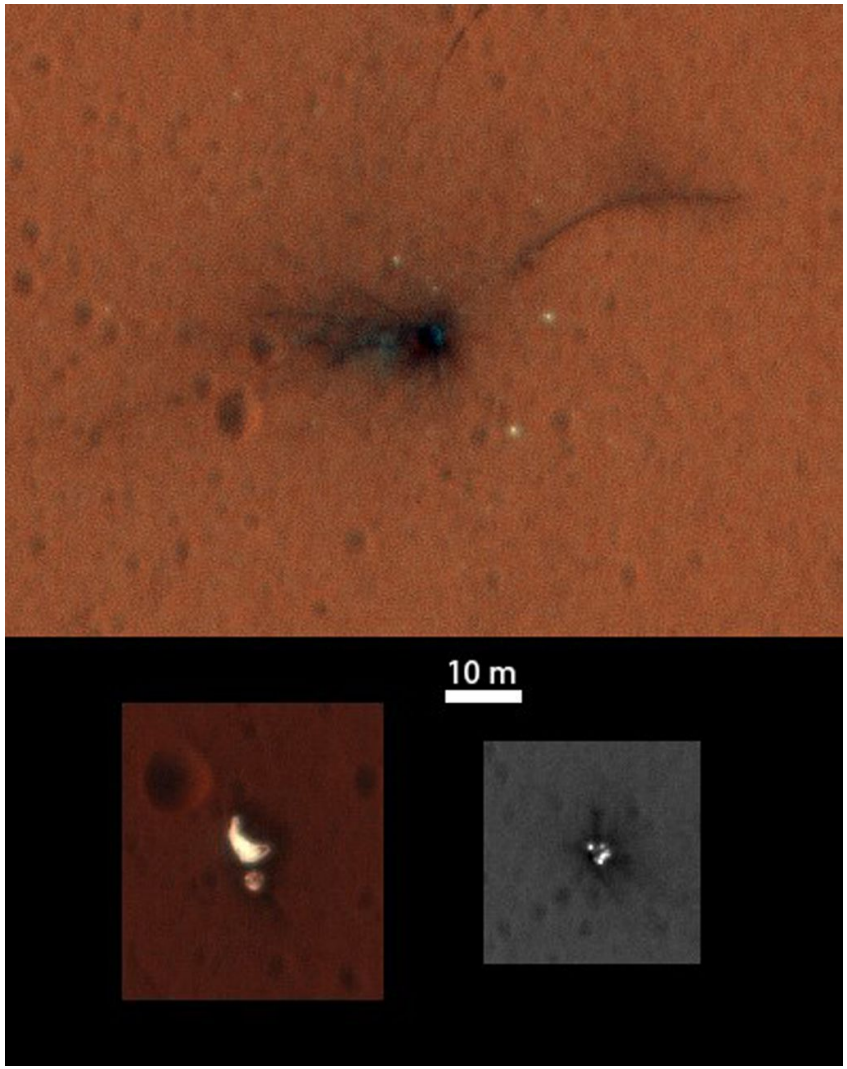


Image of Schiaparelli landing site taken by CTX after impact (October 19, 2016)

Impact Site Images Taken by MRO's HiRISE Camera



Impact site imaged on October 25, 2016



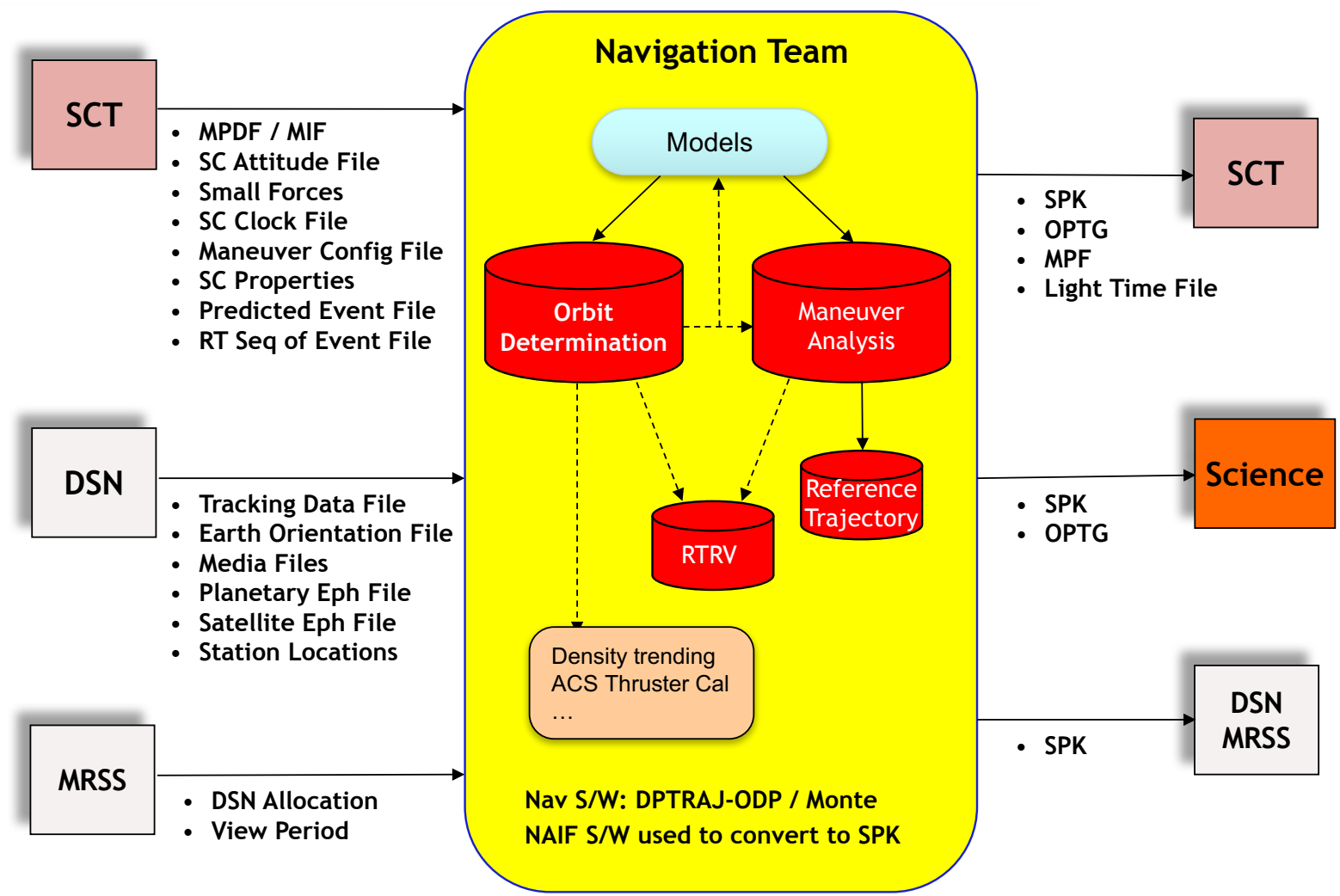
Impact site imaged on November 1, 2016

Summary

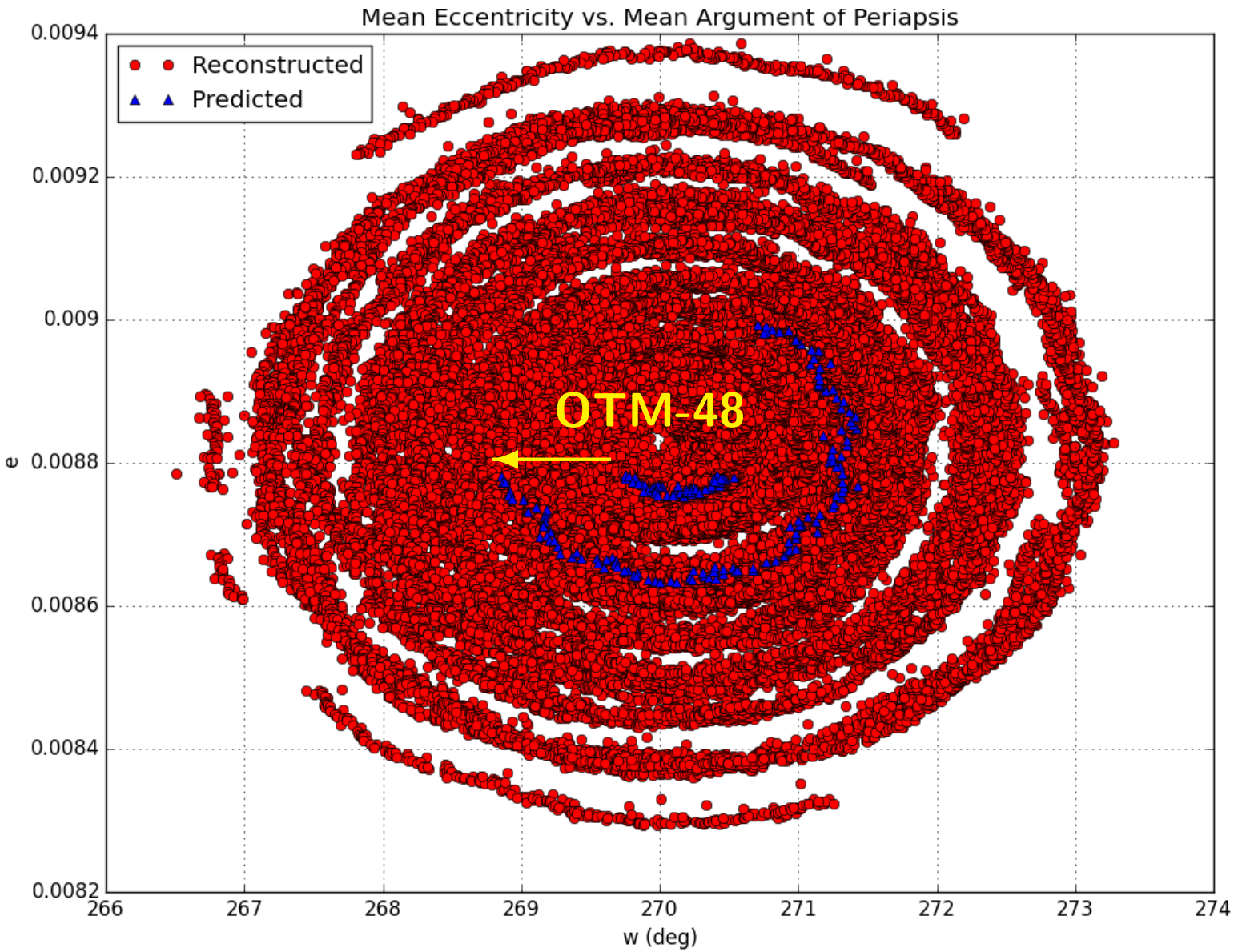
- MRO Navigation has successfully supported 10+ years of science operations to date
  - Navigation requirements were met
  - Propulsive maneuvers used for GTW control
  - Orbit Change Maneuvers used for LMST requirements
    - Most recent maneuver in preparation for InSight EDL support
  - Orbit Synchronization Maneuvers to support
    - Phoenix Lander EDL (2008)
    - Mars Science Laboratory EDL (2012)
    - Comet Siding Spring Risk Mitigation (2014)
    - ExoMars Schiaparelli Lander overflight (2016)
- Future mission support
  - Continue science operations
  - Plan EDL support for
    - InSight Mission (November 2018)
    - Mars 2020 (February 2021)
- Usable Propellant remaining – 206 kg

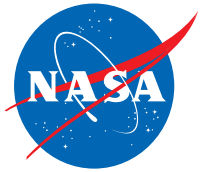
Backup Slides

MRO Navigation System & Interface



MRO's Frozen Condition





Jet Propulsion Laboratory
California Institute of Technology